

Switchless Sorption-Compressor Design

Y. Wu¹, T. Mulder¹, C. H. Vermeer¹, H. J. Holland¹, B. Benthem²,
H. J. M. ter Brake¹

¹Faculty of Science and Technology, University of Twente, Enschede, The Netherlands

²Dutch Space B. V., Leiden, The Netherlands

ABSTRACT

Sorption coolers are free of vibrations and EMI, and have the potential of a long lifetime. They are, therefore, an attractive for cooling sensitive optical detector systems in space, as well as in ground applications. Generally, gas-gap heat switches are utilized for reducing the input power in the desorption phase of the compressor sorption cycle. This is specifically required in space applications since the compressor cells are cooled by radiators which are proportional in size to the compressor input power. In terrestrial applications, such as the METIS instrument in the European Extremely Large Telescope, low input powers may not be the major concern. Especially in applications requiring both a high cooling powers and a large number of compressor cells, complexity and cost may become more important. In order to reduce these, we developed an alternative switchless sorption-compressor design using short-pulse heating. A dynamic thermal model was built for evaluating this concept and for optimizing the compressor-cell dimensions and operating parameters. This paper describes the design of compressor cells with and without heat switches, related to the METIS cooler. Furthermore, it presents experimental results on a switchless compressor that were used for validating a dynamic model. In the paper, the impact of the switchless compressor design on the METIS cooler configuration is also considered.

INTRODUCTION

A sorption-based Joule-Thomson (JT) cooler is composed of a sorption compressor and a JT cold stage [1]. Apart from a few passive check valves, a sorption JT cooler has no moving parts, which makes it attractive for various reasons. It is free of vibrations, free of EMI and it has the potential of a long lifetime. Initially, most developments of sorption coolers were done for space applications [2-4]. In space applications, the coefficient of performance (COP) of the sorption JT cooler is of great importance because it directly relates to the size of the radiator on the spacecraft. The heat switch which makes and breaks the thermal contact of the sorption cell with the heat sink is, therefore, considered an essential part. For reliability, usually, gas-gap heat switches are used for this purpose [5-7]. However, an efficient Gas Gap Heat Switch (GGHS) requires a small gas gap between the sorbent container and the heat sink (typically a few hundred microns [6]) and large heat transfer areas which are sometimes hard and expensive to achieve. Furthermore, leak tightness and outgassing requirements for the gap space are comparable to those of ultra-high vacuum systems.

At the University of Twente, a sorption-based JT cooler is under development for cooling the vibration-sensitive METIS instrument in the European Extremely Large Telescope (E-ELT) [8]. Here, the heat-sink of the sorption compressor cells will be established by a liquid-nitrogen circuit and the compressor efficiency is less important than that in space. Since the METIS cooler will be equipped with tens of compressor cells, the manufacturability and costs of the cells becomes a greater concern. We propose a switchless sorption compressor concept that greatly reduces the difficulty of manufacturing and assembly as well as the costs by sacrificing about 12 % in efficiency. This paper describes the design of the sorption compressors with and without GGHS and relates that to the METIS cooler. It then briefly discusses the dynamic modeling and more extensively the experimental validation of the model. The paper concludes by discussing the impact of the new compressor design on the cooler configuration for METIS.

SORPTION COMPRESSOR DESIGN

Sorption Compression Cycle

A sorption compressor is based on the principle that a large amount of gas can be adsorbed physically or absorbed chemically by certain solids (sorbent materials) such as activated carbon, metal-organic framework (MOF), praseodymium-cerium-oxide (PCO) or a metal hydride [9]. A single-cell sorption compressor consists of a compressor cell filled with sorption material and two buffers, as shown in Figure 1 [1]. Because the sorption cell adsorbs and desorbs the working fluid in a cyclic manner, passive check valves are required to maintain the correct flow direction through the cold stage. Furthermore, buffer volumes are applied to stabilize the pressure difference over the cold stage. As mentioned above, usually, a thermal switch is applied to thermally connect the sorption cell to a heat sink. This heat sink can be cooled by convection for ground applications, or by a radiator for space. In order to generate higher gas flows through the cold stage (and thus higher cooling powers), or for redundancy reasons, a number of cells can be used in parallel.

The cycle of a sorption compressor, as shown in an adsorption-isotherm diagram in Figure 2, can be divided into four phases that are compression, out-flow, decompression and in-flow. Starting from point 1 at initial low temperature T_l and low pressure p_l , the sorption cell is heated almost adiabatically during the compression phase (1-2 in Figure 2) while both check valves are closed. As the temperature increases, the adsorbed gas is released and the pressure in the cell container increases. In this phase, the adsorbed amount of gas per unit of mass of adsorbent, x_{ads} , decreases but the total amount of the gas in the cell remains the same. When the pressure in the

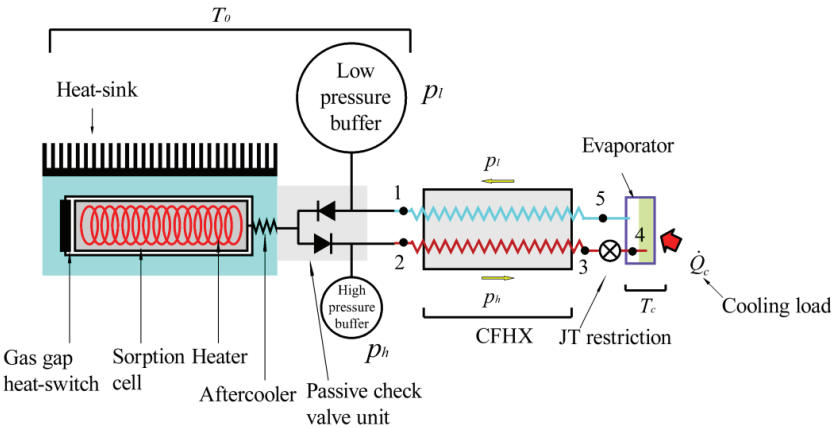


Figure 1. A basic sorption JT cooler with two buffer volumes

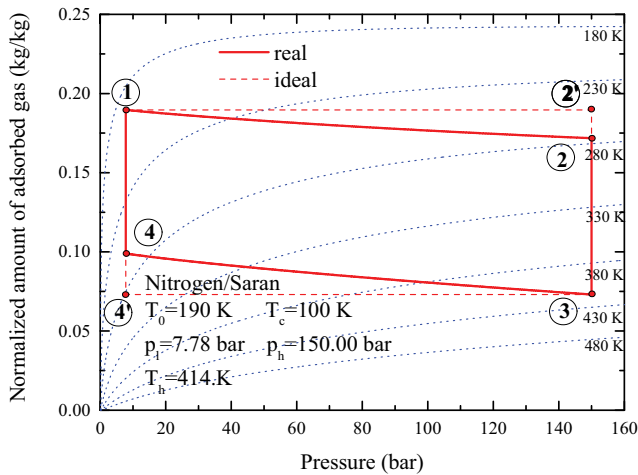


Figure 2. Example of a single-stage sorption compressor cycle operating with nitrogen and saran carbon. The blue dotted lines are the adsorption isotherms of nitrogen on saran carbon. 1-2'-3-4' shows a cycle in an ideal adsorbent. Compression phase and decompression phase will deviate from the ideal process, as depicted by process 1-2-3-4, because of the void volume in the adsorbent holding some amount of gas during the cycle.

cell rises above the high pressure p_h of the high-pressure buffer (point 2 in Figure 2), the check valve on the high-pressure side opens, and the pressurized gas flows out of the cell while the heating continues. In the out-flow phase (2-3 in Figure 2), the pressure in the cell is maintained at p_h by controlled heating. When most of the adsorbed gas is desorbed and the cell has been heated up to a high temperature of T_h (point 3 in Figure 2), heating is stopped and the cell is cooled down with the check valves closed. In the decompression phase (3-4 in Figure 2), gas is adsorbed due to the temperature decrease in the sorption cell, and the pressure in the cell container consequently drops down until the initial low pressure p_l is reached. The check valve on the low-pressure side opens in the last phase (out-flow, 4-1 in Figure 2), and the low-pressure gas from the low-pressure buffer flows into the cell and is adsorbed onto the adsorbent material while the temperature further decreases until it reaches the starting-point temperature T_l .

Gas-gap Heat Switch Configuration

The original baseline design of the sorption compressor for METIS cooler was based on a GGHS configuration, as shown schematically in Figure 3 [8]. The sorption compressor cell consists of a cylindrical container that is filled with active saran carbon. The heater is placed at the center of the carbon, and a small gas channel in the carbon reduces the axial pressure drop. A filter is used to prevent any carbon particles from flowing into the cold stage causing risk of clogging. A gas inlet tube connects the container to the tubing outside of the cell. The container

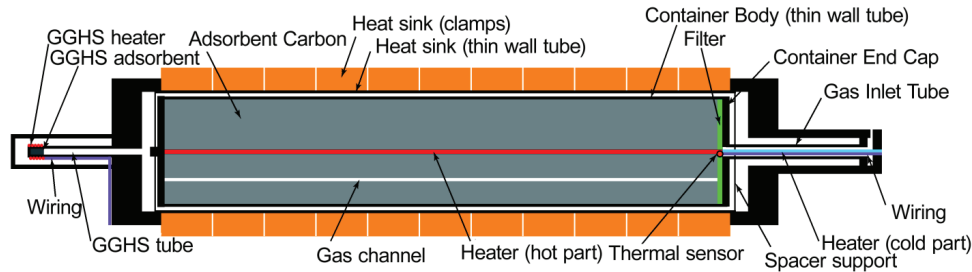


Figure 3. Schematic of a sorption compressor cooperating with a gas-gap heat switch (GGHS).

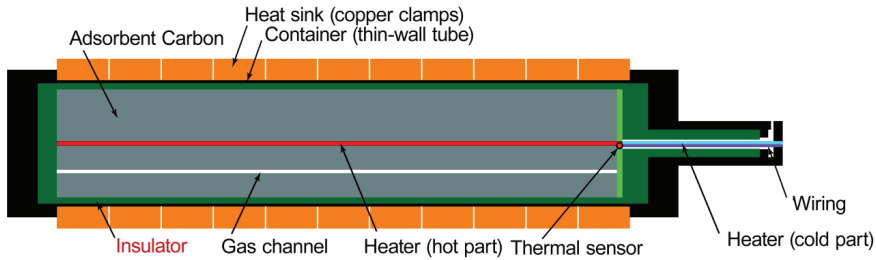


Figure 4. Schematic of a sorption compressor cooperating with a switchless insulation layer.

is thermally attached to a cryogenic heat-sink via a GGHS. Two support spacers position the container, to maintain a gap between the container and the heat-sink. At one end the gap is connected to a thin-wall GGHS tube holding a small piece of adsorbent material that actuates the conductive gas in the GGHS.

In order for the gas-gap switch to be efficient and functional, the gas-gap dimensions are strictly defined and require very high precision. In a small scale cooler for space applications, where the compressor cell is relatively short and the cell number is limited (e.g., 5 cells with a length of 10 cm for the 14.5 K hydrogen cooler in previous work [10]), the GGHS configuration is preferred for efficiency reasons. The METIS cooler, however, requires more than 50 cells, each 50 cm long. It is very difficult and expensive to realize an ultra-high vacuum quality narrow gap of 500 μm over the full length of the cell. The defect rate in the production will not be acceptable. Therefore, an alternative compressor-cell design in which the GGHS was omitted was investigated.

Switchless Configuration

In the switchless configuration for the METIS cooler, the GGHS is replaced by a switchless insulation layer as shown schematically in Figure 4. The insulation layer material requires low conductivity, low heat capacity and low porosity. Furthermore, it should be an inert material. Kapton, Mylar and Teflon are qualified candidates [11]. Kapton has the best thermal properties followed by Mylar, whereas Teflon is commercially available in a variety of geometries. Nevertheless, the solid insulation layer has a much higher conductance than the GGHS in the OFF state. A significant amount of heat will leak to the heat sink during the desorption phase (1-2-3 in Figure 2). One can simply increase the thickness of the insulation layer to reduce this conduction loss, but thicker insulation also slows down the cooling process in the adsorption phase (3-4-1) resulting in a longer cycle time and more cells required. Another way to decrease the conduction loss is rapid and short heating. However, short high-power pulse heating will generate a big radial temperature gradient in the adsorbent, resulting in a degradation of the performance.

In general, the switchless configuration will have a lower production cost and will be easier to assemble. With well optimized dimensions, the switchless configuration is expected to require more input power than the GGHS configuration, but less cells since the cycle time may be reduced.

DYNAMIC MODEL AND EXPERIMENTAL VALIDATION

Dynamic Model

In order to understand the thermal behavior of the switchless configuration and predict its performance, a dynamic thermal model was built. Although a static model was already built and used for the preliminary design of the METIS cooler [8, 12], it is not accurate in the dynamic operation of the switchless configuration. Because of the short high-power heating pulse during

the desorption phase, a large radial temperature gradient can be expected. The assumption of a uniform temperature in the static model will give quite a significant deviation from the real behavior. Furthermore, the assessment of the cycle time by the dynamic model will be more reliable than if it is estimated in the static model by a simple RC model. And the cycle time is an important parameter since it determines the number of cells required for a certain cooling power.

The dynamic model is 1-dimensional. Only the radial temperature gradient is considered, while the pressure drop through the adsorbent is neglected resulting in a spatially constant pressure. Quasi-static sorption behavior is assumed, which implies that the amount of the working fluid in the compressor cell at a particular moment in time can be calculated based on the adsorption isotherms once the pressure and temperature distributions are known.

Experiment Setup Description

To verify the dynamic model, two experiments were carried out. The first one, setup 1, is cycling a closed sorption compressor cell, building up pressure and then depressurizing it. The second one, setup 2, combines the check valves with the sorption compressor to generate a mass flow at a certain pressure difference. In both experiments, the resulting pressure and mass flow rate are measured as a function of time. The results are compared with the simulation results given by the dynamic model, to confirm its validity.

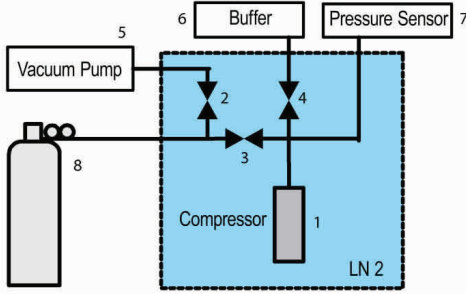
A sorption compressor cell built in a previous project shown in Figure 5 [10] was used in both experiments. It is a sorption compressor cell designed for hydrogen cooler. It uses a GGHS configuration, with a 100 μm gas gap. To simulate the switchless configuration, the gas gap was filled with conductive gas at a steady pressure which then formed the insulation layer. The original check valves were designed to satisfy space application requirements for the specific pressure and mass-flow range of the hydrogen cooler [10]. They were removed in setup 1, and replaced in setup 2 by Swagelok high-purity commercial check valves which are cheaper and more flexible in an experimental test setup.

A schematic overview and a photograph of setup 1 are presented in Figure 6 (a) and (b). The sorption compressor cell is mounted on an aluminum platform that is immersed in a liquid-nitrogen bath. The compressor cell is connected to the gas bottle, the vacuum pump and a buffer volume through valves. The system was pumped and flushed for several times before being filled to a certain initial pressure (around 4-10 bar). With all valves closed, the compressor cell was cycled by cyclic heating. A pressure wave was thus established and monitored in the volume composed of the compressor cell and some additional tubing, indicated by the blue line shown in Figure 6 (b).

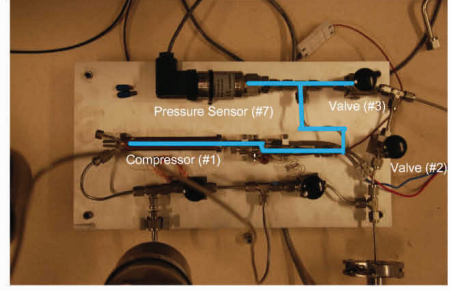
Setup 2 is presented Figure 7. Two check valves (11-12), two mass-flow meters (9-10) and a relief valve (13) were added. During the operation, the compressor pumped the working fluid from a low pressure to a high pressure. The in-flow was delivered by a gas bottle and the low pressure was regulated by a pressure regulator, while the high pressure was regulated by the relief valve and the out-flow was vented to atmosphere. The flow direction was secured by the check valves. Not only pressure, but also the in-flow rate and the out-flow rate were carefully measured during the experiment, and compared with the simulation results from the dynamic model.



Figure 5. Sorption compressor cell for 14.5 K hydrogen cooler [10]

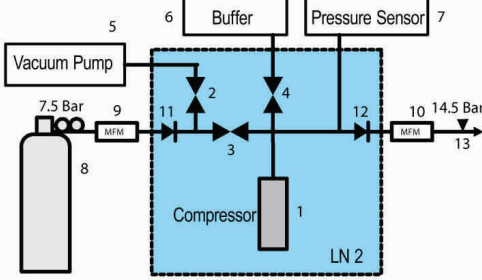


(a)

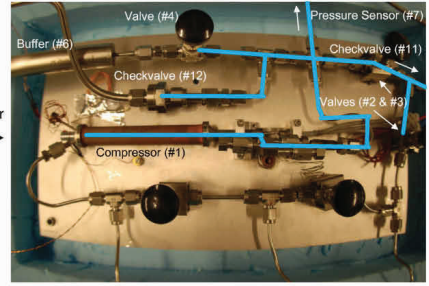


(b)

Figure 6. (a) Schematic overview of setup 1: 1.Compressor cell, 2-4.Valves, 5. Vacuum pump, 6.Buffer Volume, 7.Pressure sensor, 8.Gas bottle. (b) Photograph of setup 1, with buffer removed.



(a)



(b)

Figure 7. (a) Schematic overview of setup 2: 1.Compressor cell, 2-4.Valves, 5. Vacuum pump, 6.Buffer Volume, 7.Pressure sensor, 8.Gas bottle, 9-10.Mass flow meters, 11-12.Check valves, 13.Relief valve. (b) Photograph of setup 2.

Void Volume Evaluation

It is essential to know the parasitic void volume in the volume of interest. The parasitic void volume consists of the volume in the tubing, in the pressure sensor, and in the valves. To determine the parasitic void volume, the buffer with a known volume is connected through valve 2. The system was pumped to vacuum, then filled with helium to an initial pressure, p_i , with valve 2 closed. Then valve 2 was opened, letting the helium flow into the buffer volume resulting in a pressure drop to a final pressure, p_f . In this process, the mass of helium was constant,

$$m_{He} = m_{carbon} x_{tot}(T, p_i) + \frac{p_i V_{void} M}{RT} = m_{carbon} x_{tot}(T, p_f) + \frac{p_f (V_{void} + V_{buffer}) M}{RT} \quad (1)$$

Solving Eqn. (1), the void volume can be readily determined,

$$V_{void} = \frac{\frac{m_{carbon} RT}{M} [x_{tot}(T, p_i) - x_{tot}(T, p_f)] - p_f V_{buffer}}{p_f - p_i} \quad (2)$$

By this method, the void volumes of both setup were measured and considered as an important correction parameter in the simulation.

Experimental Results and Discussion

Typical measurement results for setup 1 are presented in Figure 8. A square heating pulse of 30 W was used in the measurement for different heating times. In the helium measurement, the pressure recording matches the simulated pressure very well for short heating cases. However,

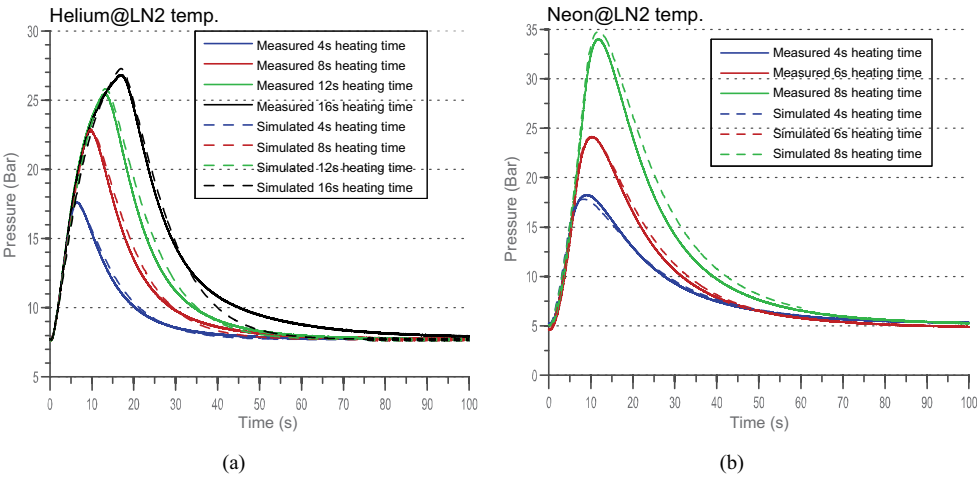


Figure 8. (a) Pressure in the compressor cell for setup 1, operating with helium gas. Initial filling pressure is 7.7 bar, and several runs with different heating times are shown in the figure. Square heating pulse of 30 W was applied in all cases. (b) Pressure in the compressor cell for setup 1, operating with neon gas. Initial filling pressure is around 5 bar.

the deviation increases when the heating time increases, especially at the cooling down phase. This is explained by the deviation in the heat-sink temperature. The total input heat of the heating pulse will be eventually dumped into the heat-sink. A longer heating time results in a larger input heat. As demonstrated in the experiment, it causes an increase in the heat-sink temperature. Consequently, the cooling down process slowed down, so that the pressure dropped slower than in the simulation where a constant heat-sink temperature was assumed. More neon can be adsorbed on the saran carbon compared to helium at the same liquid-nitrogen temperature. Therefore, the initial filling pressure was around 5 bar and the heating time was limited up to 8 s, to prevent a too high pressure during the operation. The neon measurement results match the simulated results in a large time range.

Figure 9 presents the pressure and mass-flow rate in setup 2 for a single cycle operation. The initial filling pressure was 9.2 bar, the relief valve was set at 14.5 bar and the working fluid was helium. Pulse heating was 30 W and lasted for 12 s. The pressure in the compressor increased rapidly. Because the cracking pressure of the check valve is smaller than that of the relief valve the check valve opens at around 14.8 bar while the relief valve was still closed. A small out-flow

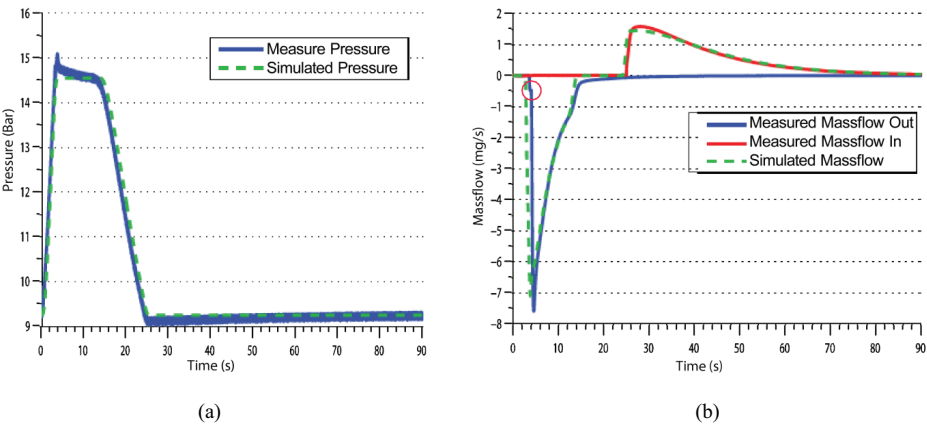


Figure 9. (a) Pressure in the compressor for setup 2 run with helium gas, 30 W heating for 12 s. (b) Mass flow rates for setup 2.

step was first measured at that moment, and is indicated by the circle in Figure 9(b). The relief valve was open when the pressure increased up to 15.1 bar, a peak out flow was then generated accompanied with a pressure drop back to 14.5 bar, the relief valve setting value. However, in the simulation the cracking pressures of the check valve and the relief valve were not taken into account which explains the fact that the simulated flow started earlier than the measured flow. Integrating the mass flow over a cycle, a total amount of 34.2 mg helium gas was pumped in a cycle in the measurement while 35.2 mg in the simulation. The relative error is only 2.9%.

Another measurement included multiple cycles with a fixed cycle time. The measured mass flow rate versus time is shown in Figure 10. The cycle time was set to 90 s. Note that the mass-flow peak decreased slightly each cycle. That is due to the liquid-nitrogen level dropping during the experiment. The heat-sink temperature increases slowly resulting in a slight performance degradation. However, the measurement results agree with the simulation very well.

In summary, the dynamic model is validated by the experiments, and can be applied to predict the performance of the sorption compressor cell in the compressor system of the METIS cooler.

METIS COMPRESSOR SYSTEMS

Based on the operating condition optimization [8], the detailed dimensions of the switchless sorption compressor for METIS cooler were optimized. The results are presented in Table 1.

In order to compare the performance of the METIS cooler with and without GGHS, the dynamic model was adapted to also evaluate the GGHS configuration. A performance comparison was made, and the results are shown in Figure 11. For the hydrogen stage and the helium stage, the switchless configuration requires more power and fewer cells than the GGHS configuration, as expected. However, for the neon stage the switchless configuration performs better. This is explained by the fact that the high pressure of the neon cooler stage is above 100 bar. Therefore, the cell container is relatively thick, and considerable heat is wasted in heating

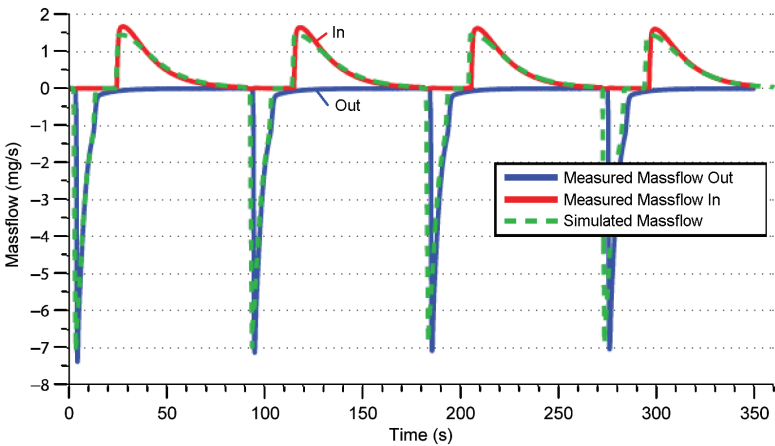


Figure 10. Mass flow rate along time in a four cycle run for setup 2

Table 1. Dimensions of the switchless sorption compressor for METIS cooler

Dimensions	Unit	Neon stage	Hydrogen stage		Helium stage
			1 st stage	2 nd stage	
Container wall thickness	mm	1.30	0.40	0.40	0.25
Insulation thickness	mm	2	1.5	2	1.25
Material of the insulation	-	Kapton	Kapton	Kapton	Kapton
Diameter of the adsorbent	mm	14.5	14.5	14.5	14.5
Length of the cell	cm	50	50	50	50

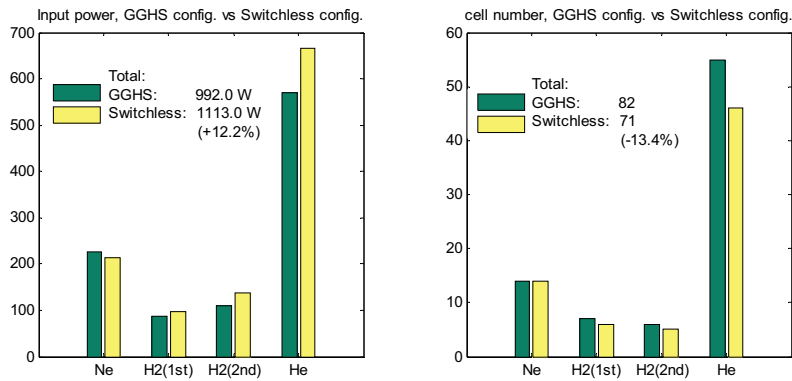


Figure 11. Input power and cell number comparison, GGHS configuration (green bars) versus switchless configuration (yellow bars).

the container wall. In total, the switchless configuration uses 12.2% more input power, but it requires 13.4% less cells and it is much easier to manufacture and assemble. Therefore, the baseline design of the METIS cooler now uses switchless cells as specified in Table 1.

SUMMARY

In this paper, we propose a switchless sorption compressor configuration for the cooler of the METIS instrument in E-ELT. A dynamic model was built and experimentally verified for simulating this new configuration and predicting the performance of the compressor. The model is used to adapt the design of the METIS cooler. Compared to the original configuration with a GGHS, it requires 12% more input power but 13% less cells, and it greatly reduces manufacturing difficulties and production costs.

ACKNOWLEDGMENT

This research is enabled through the Netherlands Research School for Astronomy (NOVA) by financial support from the Netherlands Organization for Scientific Research (NWO) under contract 184.021.006.

REFERENCES

1. Wiegerinck, G.F.M., Burger, J.F., Holland, H.J., Hondebrink, E., terBrake, H.J.M., Rogalla, H., "A sorption compressor with a single sorber bed for use with a Linde-Hampson cold stage," *Cryogenics* Vol. 46 Issue: 1: (2006), pp. 9-20.
2. Burger, J.F., *Cryogenic microcooling*, [Ph.D thesis], University of Twente, Enschede, The Netherlands, 2001.
3. Burger, J.F., ter Brake, H.J.M., Holland, H.J., Meijer, R.J., Veenstra, T.T., Venhorst, G.C.F., et. al., "Long-life vibration-free 4.5 K sorption cooler for space applications," *Review of Scientific Instruments*, Vol. 78 (6): (2007), pp. 065102-065110.
4. Bhandari, P., Prina, M., Bowman Jr., R.C., Paine, C., Pearson, D., Nash, A., "Sorption coolers using a continuous cycle to produce 20 K for the Planck flight mission," *Cryogenics* Vol. 44 (6-8): (2004), pp. 395-401 .
5. Chan, C.K., "Improved heat switch for gas sorption compressor," *NBS Proc. of the 3rd Cryocooler Conf.*, National Bureau of Standards, Boulder, CO, USA (1985): pp. 42-52.

6. Burger, J.F., Holland, H.J., van Egmond, H., Elwenspoek, M., ter Brake, H.J.M., Rogalla, H., "Fast Gas-Gap Heat Switch for a Microcooler," *Cryocoolers 10*, Plenum Publishing Corp., New York (1999), pp. 565-574.
7. Prina, M., Bhandari, P., Bowman, R.C., Paine, C., Wade, L.A., "Development of gas gap heat switch actuator for the PLANCK sorption cryocooler," *Adv. in Cryogenic Engineering*, Vol. 45B, Kluwer Academic/Plenum Publishers, New York (2000), pp. 553-560.
8. Wu, Y., Vermeer, C.H., Holland, H.J., Doornink, J., Benthem, B., Boom, E., et. al., "Sorption-based vibration-free cooler for the METIS instrument on E-ELT," *Adv. in Cryogenic Engineering*, Vol. 59, Amer. Institute of Physics, Melville, NY (2014), pp. 142-147.
9. Wade, L.A., "An Overview of the Development of Sorption Refrigeration," *Adv. in Cryogenic Engineering*, Vol. 37B, Plenum Publishing Corp., New York (1992), pp. 1095-1106.
10. ter Brake, H.J.M., Burger, J.F., Holland, H.J., Meijer, R.J., Mudaliar, A.V., Zalewski, D., et. al., "14.5 K Hydrogen Sorption Cooler: Design and Breadboard Tests," *Cryocoolers 16*, ICC Press, Boulder, CO (2011), pp. 445-454.
11. J. Ekin, *Experimental Techniques for Low-Temperature Measurements*, Oxford, UK: Oxford University Press; 2006.
12. Wu, Y., Zalewski, D.R., Vermeer, C.H., ter Brake, H.J.M., "Optimization of the working fluid for a sorption-based Joule-Thomson cooler," *Cryogenic*, Vol. 58: (2013), pp. 5-13.